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Remote Sensing -- A Scientific Vision for Sustainable Development

Tilting Effect on the Derivation of Wind Speed from Satellite Altimeters

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Abstract – The tilting effect (caused by water waves that are much longer than the radar waves) modifies the local radar incidence angle and introduces a strong attenuation of the radar backscattering return. It is shown that when this tilting effect is accounted for, the agreement of the wind speed derived from the altimeter with the buoy measurement of wind speed is significantly improved.

INTRODUCTION

Feasibility of deriving the wind speed at the sea surface from satellite altimeter data has been convincingly demonstrated during the past two decades with output from GEOS, SEASAT, GEOSAT and most recently TOPEX/POSEIDON missions. The basis for relating radar measurements to wind speed is that the radar backscattering intensity is dependent on the surface roughness and that in the ocean, the surface roughness is mainly caused by wind-generated surface waves. The measured radar intensity (the normalized radar cross section), σ_0, however, was found to differ significantly from theoretical calculations using equations derived from scattering processes (e.g., [1]) and measured physical properties of the surface roughness (e.g., [2]). Most puzzling of all, calculations consistently indicated that the sea surface detected by radars, with wavelengths on the order of a few centimeters, was "rougher" than those detected by optical instruments that depend on light with wavelengths in the sub-micrometer wavelength range (Fig. 1).

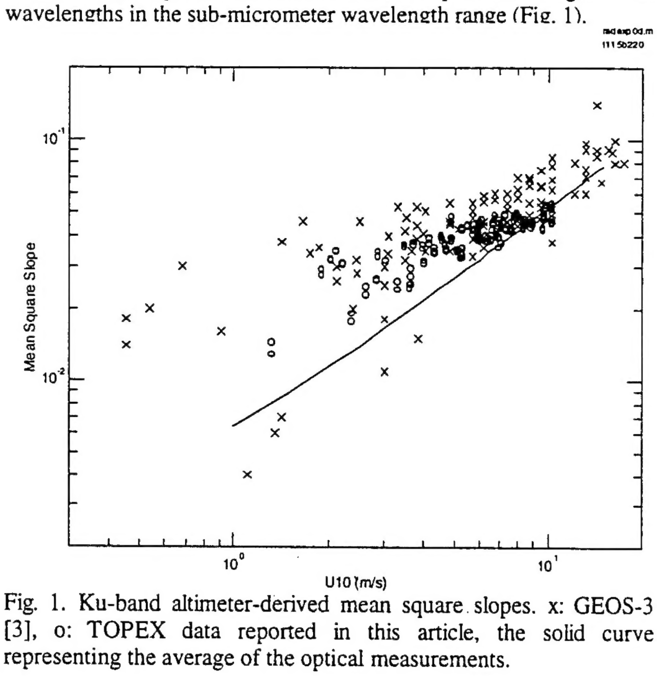

Fig. 1. Ku-band altimeter-derived mean square slopes. x: GEOS-3 [3], o: TOPEX data reported in this article, the solid curve representing the average of the optical measurements.

This perplexing result was not resolved in the past two decades since the advent of altimeter data. Up to this stage, the majority of wind speed algorithms are based on empirical or statistical analyses, most of them rely on the correlation of coincident and collocated databases of the satellite radar cross section and in-situ wind speed (e.g., [4-6]). One algorithm [7] relies completely on the independently derived statistical properties of the altimeter backscattering cross section and sea surface wind speed. The difference among these algorithms are relatively minor. It is shown that the tilting effect (caused by water waves that are much longer than the radar waves) modifies the local radar incidence angle. The change of local incident angle results in an exponential attenuation of the radar return. When this tilting effect is accounted for, the agreement of the wind speed derived from the altimeter with the buoy measurement is significantly improved.

TILTING EFFECT

A conceptual sketch to illustrate the tilting effect is shown in Fig.2 [8]. The sketch illustrates a train of plane waves (indicated by the parallel wave front) impinging on the water surface, corresponding to the scattering of the far-field radar waves from satellite altimeters. The scattered wave patterns from the water surface will vary according to the surface roughness conditions, been more directional and narrowly distributed from a smooth surface, as in patch 1. The primary direction of the scattering pattern is along the direction of specular reflection. Therefore, for surfaces of equivalent roughness, such as patches 2, 3 and 4, the scattering patterns are similar in the directional distribution (the beam width, determined by the surface roughness), but the primary direction of the scattering will vary depending on the orientation of the roughness patch. The backscattering intensities, that is, the scattering in the direction opposite to the incoming waves, for the three patches shown will be different. The modification of the local incident angle results in a reduced, or attenuated, radar return compared to the condition when the scattering is assumed to be on a flat surface such as depicted in patch 5. The concept illustrated in Fig. 2 forms the basis of this paper regarding the tilting effect on the altimeter scattering from the ocean surface.

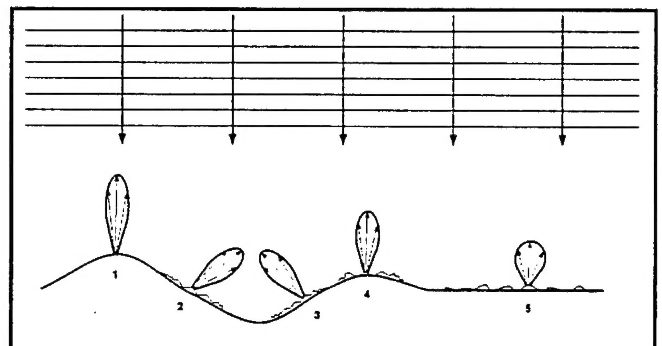

Fig. 2. A conceptual sketch illustrating the scattering of radar waves by surface roughness.

For monostatic radar applications, that is, projecting and receiving radar waves with the same antenna, backscattering properties are of most interest. The backscattering intensity is generally expressed as the normalized radar cross section (NRCS), σ_0. Many expressions of σ_0 have been presented in the literature. The major differences of their results are the assumptions of the surface roughness and the

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dielectric constant of sea water, which determines the refractive index of the sea surface. For radar altimeter applications, the expression given in [1] is frequently employed (assuming a Gaussian distribution of the scattering surface roughness)

$$\sigma_o(\theta_i) = \frac{|R(0)|^2}{s_f^{\ 2}} \sec^4 \theta_i \exp\left(\frac{-\tan^2 \theta_i}{s_f^{\ 2}}\right), \tag{1}$$

where θ_i is the radar incidence angle, denoting the angle between the propagation direction of radar waves and the surface normal; $|R(0)|^2$ is the Fresnel reflection coefficient, characterizing the surface reflectivity; and s_f^2 is the filtered mean square slope, representing the portion of surface roughness elements with length scales greater than the diffraction limit. Eq. (1) corresponds to the zero-th order solution of the scattering of electromagnetic waves from a rough surface. With a normal incidence, θ_i=0, (1) can be expressed as

$$\sigma_o(0) = \frac{|R(0)|^2}{s_f^{\ 2}}. \tag{2}$$

Introducing the concept of local incident angle (e.g., [9-10]), (1) can be expressed as

$$\Sigma_o(\theta_i) = \int \frac{|R(0)|^2}{s_f^{\ 2}} \sec^4(\theta_i + \theta) \exp\left(\frac{-\tan^2(\theta_i + \theta)}{s_f^{\ 2}}\right) p(\theta) d\theta, \tag{3}$$

where θ is the slope of the long wave roughness (the tilting waves) that contributes to the modification of the local incidence angle, $p(\theta)$ is the probability density distribution (pdf) of the tilting waves, and Σ_0 is the expected radar cross section measured by the altimeter. For normal incidence, θ_i=0, and (4) becomes

$$\Sigma_o(0) = \int \frac{|R(0)|^2}{s_f^{\ 2}} \sec^4 \theta \exp\left(\frac{-\tan^2 \theta}{s_f^{\ 2}}\right) p(\theta) d\theta. \tag{4}$$

Comparing (2) and (4), the analytical form of the attenuation factor, $\Delta\sigma_0$, due to the tilting effect can be assessed by the ratio of Σ_0 and σ_0

$$\Delta\sigma_0 = \frac{\Sigma_o(0)}{\sigma_0(0)} = \int \sec^4 \theta \exp\left(\frac{-\tan^2 \theta}{s_f^{\ 2}}\right) p(\theta) d\theta. \tag{5}$$

Fig. 2 shows a comparison of computational results using (2), shown as dashed curve, and (5), shown as solid curve, with the TOPEX Ku-band altimeter data, shown as circles. The agreement with the altimeter data with the consideration of the tilting effect is significantly improved.

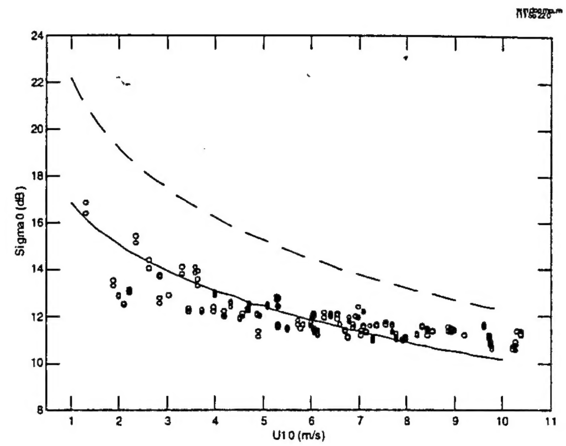

Fig. 3. Tilting effect on the altimeter cross section.

COMPARISON WITH BUOY MEASUREMENTS

Two different wind speed algorithms are developed in [8, 11] to account for the tilting effect. The first (Tilt-ALT) is an operational algorithm that calculate the wind speed directly from the altimeter cross section, and the second is a research algorithm (Tilt-Surface) that assumes a prior knowledge of the tilting slopes in order to correct the altimeter cross section (5). Comparison in term of the distributions of the wind speed difference between in-situ buoy data and altimeter measurements based on five different algorithms are presented in [11]: the two mentioned above plus the empirical algorithms of Brown et al. (B81) [4]; Modified Chelton and Wentz (MCW) [6]; and the statistical algorithm of Freilich and Challenor (F&C) [7]. Typically, the distributions of the first three empirical algorithms are quite similar. For example, one case study (Fig. 4) shows the following statistics: the rms difference and the correlation coefficient are (1.41 m/s, 0.81), (1.39 m/s, 0.81) and (1.51 m/s, 0.81), respectively for B81, MCW and F&C. The statistical properties of the wind speed difference based on the operational algorithm (Tilt-ALT) are very similar to the other three algorithms just discussed, the rms difference and the correlation coefficient are (1.49 m/s, 0.80). However, if the tilting slope can be accurately calculated, and the correction to the measured cross section applied properly, the distribution of wind speed difference is noticeably narrowed. The rms difference and the correlation coefficient improve significantly to (0.84 m/s, 0.96). Similar improvements are found with other data sets we have compiled in the Gulf of Mexico. Table 1 lists the rms differences and the correlation coefficients of the surface wind speed comparisons using the 5 algorithms just described. We may conclude from this comparison that the accuracy of the satellite altimeter is considerably better than we have previously accepted. If independent measurement of the tilting slope is available, the rms difference between the altimeter output and in-situ measurements will be reduced from the currently accepted magnitudes established by empirical algorithms. The improvement is approximately 40 percent based on the results shown in Table 1. And most significant of all, this conclusion is based on sound physical ground relating the altimeter backscattering and the surface slope properties, unlike the earlier operational algorithms that depend on empirical formulae established from co-located buoy and altimeter databases.

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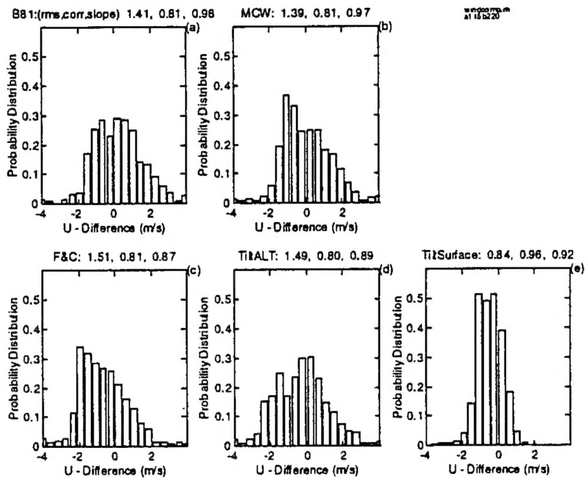

Fig. 4. The distributions of wind velocity differences (ALT - Buoy) for the five algorithms discussed in this article. (a) B81 [4]; (b) MCW [6]; (c) F&C [7]; (d) TiltALT [8], and (e) TiltSurface [8].

Table 1. Comparison of the rms difference and correlation coefficient of buoy winds and altimeter winds [11].

(a) RMS (m/s)

	B81	MCW	F&C	Tilt-ALT	Tilt-Surf
A115B220	1.41	1.39	1.51	1.49	0.84
A21B220	1.28	1.35	1.62	1.58	0.97
A46B203	1.75	1.74	1.79	1.83	1.07
A59B202	1.30	1.14	1.33	1.56	0.86
A46B236	1.30	1.36	1.46	1.41	0.80
A26B202	2.73	1.45	1.52	1.65	1.21

(b) Correlation Coefficient

	B81	MCW	F&C	Tilt-ALT	Tilt-Surf
A115B220	0.81	0.81	0.81	0.80	0.96
A21B220	0.90	0.90	0.90	0.89	0.97
A46B203	0.82	0.83	0.83	0.81	0.95
A59B202	0.92	0.93	0.93	0.91	0.98
A46B236	0.90	0.91	0.91	0.90	0.98
A26B202	0.65	0.88	0.87	0.80	0.91

CONCLUSIONS

In the course of studying the wind speed derivation from satellite altimeters, it is found that the surface tilting effect is a significant factor of consideration. The effect is especially noticeable at lower wind velocities where differences of more than 6 dB are found between the altimeter measurements and the computations using the classical equation relating the backscattering cross section and the surface roughness (2). With the correction of the tilting effect in the cross section measurement, the calculated wind speed is found to be in much better agreement with the surface buoy measurement. The improvement is on the order of 40 percent when compared to the results derived from other statistical or empirical algorithms including B81, MCW and F&C. This result suggests that the theoretical frame work relating the backscattering cross section and the surface roughness is fundamentally sound when the tilting effect that modifies the local incident angle is taken into account. It also indicates that the accuracy of deriving wind speeds from altimeter cross sections is potentially much better than we have perceived, however, in order to achieve the full potential of the altimeter wind sensing, independent measurement of the sea surface slope component contributing to the tilting may be needed.

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